# NOTES ON POSSIBLE PART 15/TELETRAC INTERFERENCE TESTS

## Introduction

The purpose of the set of tests proposed here is to develop a quantitative understanding of the potential for interference from Part 15 devices into the receivers used in PacTel Teletrac's vehicle location system in the 902-928 MHz band.

There are several components that determine whether harmful interference occurs:

- The performance of the Teletrac receiver (e.g., rms time-of-arrival estimation error as a function of various desired and interfering signal levels).
- Propagation path loss for various scenarios of interest (different transmitter and receiver elevations, separations, and terrain characteristics).
- Timing characteristics of the interfering signal and the Teletrac reverse link. For example, a frequency-hopping Part 15 device will not always be transmitting within the RF bandwidth of the Teletrac receiver, and the Teletrac system can re-transmit if the received signal is too corrupted.

Each of these components is discussed individually below.

## Teletrac Receiver Performance

The function of the Teletrac receiver is to generate an estimate of the TOA (time of arrival) of the wideband burst from the vehicle. One way of quantifying receiver accuracy is the rms TOA estimation error. The rms error depends on the carrier-to-noise or carrier-to-interference ratio, as shown in Figure 12 of Appendix 2 to Teletrac's Comments on the NPRM in PR Docket 93-61, attached here as Fig. 1.

The first step of the experimental program should be a more complete characterization of the Teletrac receiver. The curve in Fig. 1 characterizes the receiver only for a carrier-to-noise ratio (CNR) down to -25 dB, and the noise power was set at -80 dBm. The TOA estimation error should be determined for CNR levels less than -25 dB (which apparently is the threshold of the Teletrac receiver). The error also should be measured as a function of the CNR for higher noise power (e.g., -40 dBm), to explore AGC and A/D dynamic range effects.

The receiver performance characterization probably is the most important component of the experiment, since the effects of the other two factors (propagation and timing characteristics) can easily be investigated via analysis and/or simulation. Fortunately, receiver performance measurements can be made on the bench, using known and controlled desired and interfering signals.

A further step would be to introduce multipath effects into the bench test via a fade simulator, to characterize the impact of different multipath delay profiles on the rms TOA estimation error.

### Propagation Path Loss

Path loss is important because it determines the strength of the desired and interfering signals received by the base station. The technical literature is rich with papers discussing propagation phenomena and models for a wide variety of frequencies, terrain conditions, and applications. Empirical models have been developed based on analysis of measurement data, and models also have been built directly from electromagnetic theory. In most circumstances, propagation path loss must be viewed statistically because of the random factors (multipath, shadow fading) that influence it. Because of this statistical nature, measurement programs typically involve many thousands of individual data points to accurately characterize propagation behavior. As a result, they tend to be fairly tedious and time-consuming, and require a certain degree of specialized equipment and expertise to perform reliably.

To draw general conclusions about the interference problem, we probably should use some of the existing propagation models based on the published work of experts in the field. The alternative is to conduct our own propagation measurement program, which would be time-consuming and probably not very enlightening. Of course, if we conduct field tests, we will need to make isolated measurements of the received signal strength for specific paths to determine the levels of the desired and interfering signals, and we should note the approximate distances from the receiver of the desired and interfering transmitters.

### Timing Factors

If the interfering signal does not continuously overlap the Teletrac reverse link passband, then "time diversity" (re-transmission) can help to mitigate the effects of interference (although it will reduce throughput). Time diversity may work if the interfering device is a frequency hopper, but the relationship between the re-transmit interval and the hopping rate will be a factor. If there are multiple hoppers near multiple bases, the statistics of the problem rapidly become quite complicated and will be difficult to characterize fairly with a simple experiment. However, analysis of the situation would be fairly straightforward once all the parameters are known. Therefore, measurements should use a continuous interfering signal to determine the inherent receiver susceptibility, and transmission timing should be taken into account by analysis.

### Conclusions

The first part of the test program should be a more thorough characterization of Teletrac's receiver. Without this, it may be difficult to correctly interpret field test results. Such a characterization should be fairly straightforward on the bench using an approach similar to that described by Teletrac in Appendix 2 of its Comments. However, the effects of a larger range of CNR and higher noise (and carrier) power need to be explored. In addition, multipath effects could be introduced using a fade simulator. If time is extremely critical, many useful and valid conclusions could be drawn from such measurements using existing propagation data and models. If time allows, field experiments of interference effects associated with different interfering and desired signal source positioning could be conducted. The strength of the interfering and desired signals at the receiver should always be measured, so results can be checked against the receiver bench tests.

The effects of time-diversity and fractional duty cycles of the interfering signals (such as those from frequency hoppers) will be difficult to characterize completely with experiments, but can be understood easily with analysis. Therefore, the field tests should use fixed-frequency transmitters to simulate the interference sources. The results can easily be extrapolated to account for time variations.

## POSSIBLE PROGRAM OUTLINE

Based on the considerations discussed above, one possible set of steps is:

1. Assemble interested parties, review proposed plan, add detail, determine participants, develop schedule.
2. Conduct bench tests of Teletrac's receiver for CNR ranging from -15 dB to -40 dB and noise from -40 dBm to -80 dBm in 5 dB increments (no multipath).
3. Repeat (2) but introduce multipath with a fade simulator. Explore effect of multipath for delay spreads up to 25 $\mu$s. Make detailed measurements over a range of CNR for cases of interest. [More detail to be added during planning meeting.]
4. Select a single Teletrac receiver site that will allow a controlled variation in the positioning of both the interfering and desired signal sources. Set up a test control system that will allow the desired transmitter (in a vehicle) to repeatedly transmit its signal on command. This will allow enough samples to be taken to support a statistically valid determination of the rms TOA estimation error. Received signal levels for the vehicle and the interference source should be recorded. Take sample sets of TOA estimation error and signal strength measurements for desired positions of vehicle and interference source. [Details of test conditions to be added during planning meeting.] Note: with the complete bench characterization of the receiver, and knowledge of the path loss characteristics for the scenario of interest, these measurements are not completely necessary, but they may serve as useful confirmation of predicted results.
5. Share relevant information on timing characteristics of potential interference sources, and retransmission (time diversity) discipline of Teletrac's system. Using this timing information and the results of the tests discussed above, compute the effect of interference on system throughput for scenarios of interest.
6. Prepare report summarizing problem, outlining general approach, reviewing procedure and equipment, showing data, summarizing results/conclusions, and identifying any remaining open issues.

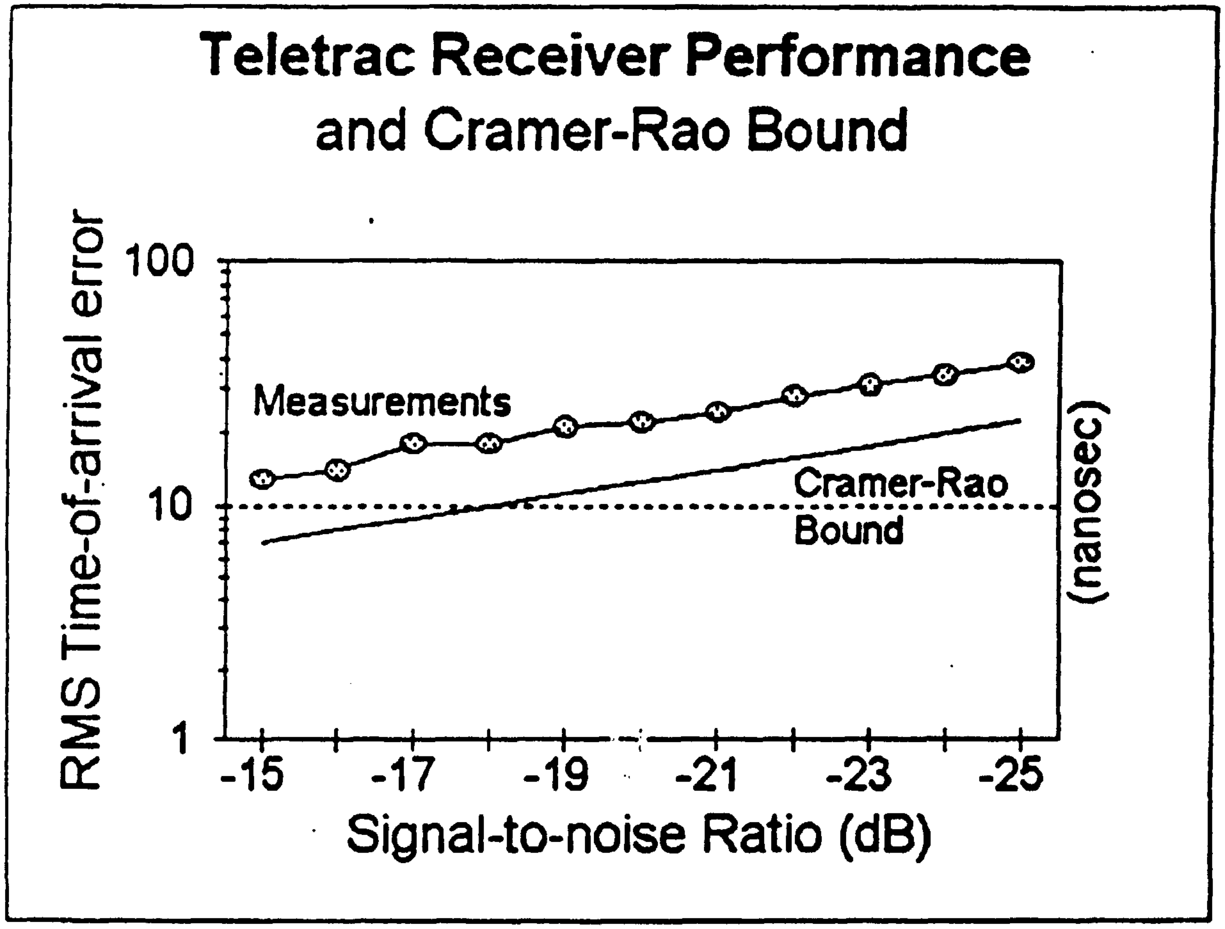


Figure 1

(reproduced from Appendix 2 of Teletrac's Comments, Fig. 12)

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TELETRAC

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December 22, 1993

Dr. Jay Padgett
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Dear Jay:

CZ asked me to respond to your letter dated November 24, regarding the continuation of the process to assess the potential interference between Part 15 units and the Teletrac system, as well as Part 15 units among themselves.

We are confident that our system can operate under reasonable conditions in a band shared with units operating under Part 15, reasonable being defined by the interference level that these devices can tolerate themselves. To test this assumption, the amount of interference created by Teletrac to Part 15 units, Part 15 units to Teletrac and part 15 units among themselves can be determined by means of a statistical simulation, once the data is available and the scenarios agreed upon.

To this day, PacTel Teletrac has been the only company providing data that can be used to implement such simulation. The location of our sites is also available. The models for RF propagation in the urban and suburban environments are well known and documented in literature. The missing inputs for the simulation are the data regarding devices operating under Part 15 in the 902-928 MHz band.

We have not yet received technical information regarding such Part 15 devices. Accurate information is mandatory if the simulation is to be valid and useful. Since you chair the TIA Mobile and Personal Communications Committee dealing with Part 15 cordless phones, I am confident that you can explain to your partners on the Committee the importance of information that will support assessment of the quality of the service their customers may expect. You may also have good contacts with other Part 15 manufacturers and, if this is so, could help the process by providing

To provide the correct picture of service availability, the simulation will have to consider the capability of each unit to operate within its acceptable operational parameter, i.e., as a communication user; to estimate the capability of other such users to operate, the simulation has to estimate the level and type of noise present at the input of each unit, primarily due to the signals emitted by all devices in their role as sources of interference. Therefore, the information that each manufacturer should provide should include all data required to consider its devices as users and interferers. A preliminary list of such data includes:

- Operating frequency (or frequencies) and frequency plan
- Transmitted power
- Antenna gain (a statistical antenna pattern may be required for a realistic 3D simulation)
- Sensitivity of the receiver (performance as a function of SNR) in the presence of in-band and adjacent channel interference
- Modulation scheme and symbol rate
- In-band and out-of-band spectral characteristics
- Sequence of communication events, their duration and respective statistics. It is important to identify failure conditions and recovery procedures for each event.
- Typical scenarios in terms of distribution of units in urban and suburban environments, in- and out-of-building deployments, antenna heights and distance between units comprising a link.

As soon as the information is collected, I recommend we get together to define the extent, resources and schedule of the simulation. My direct-dial office telephone number if 310-338-7192.

Sincerely yours,

Yair Karmi
Vice President
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January 4, 1994

Dear Yair,

This is in response to your letter of December 22 (attached), in which you solicit specific technical characteristics of various Part 15 devices as input data to a computer simulation. Unfortunately, I do not have access to the detailed information you seek. Moreover, there are undoubtedly Part 15 devices planned for the 902-928 MHz band, or even already deployed, of which I am unaware. Therefore, I believe the most effective means of information exchange between Teletrac and the Part 15 community would be a meeting for the planning of whatever experiments and/or simulations are needed.

Clearly, a computer simulation is one tool that can be used to assess the impact of Part 15 interference on Teletrac's system. One problem with this approach is that it can become quite complex when many different devices and characteristics are involved. In addition, it can be difficult to perform "sanity checks" on complex simulation results to determine whether a result is realistic, or whether it arises from a programming error or some numerical anomaly. I therefore believe that as a prelude to any such simulation, we should jointly plan a set of fairly simple tests that involve only a single Teletrac receiver, rather than the entire system. If the results of those tests indicate that a more complex simulation is warranted, the test results can serve as a benchmark against which the simulation results can be checked.

As discussed in the notes on interference tests which I included with my November 24 letter to CZ, probably the first, and most critical step of this process, is a complete characterization of the Teletrac receiver. Contrary to the implication in paragraph 3 of your letter, Teletrac has not provided the data necessary to support a complete assessment of the potential for interference with the operation of its system by Part 15 devices. While a receiver characteristic was shown in Fig. 12 of Appendix 2 to Teletrac's Comments in PR Docket 93-61, it was limited to a carrier-to-noise ratio (CNR) only down to -25 dB, and the noise power was -80 dBm. Characterization also is needed for CNR levels below -25 dB, and for higher noise and interference power levels (e.g., -40 dBm) to explore AGC (automatic gain control) and A/D (analog-to-digital) converter dynamic range effects. This could be done in the lab rather than the field, and should not require a substantial amount of time. I believe it would involve an equipment setup similar to that used to generate the data shown in Teletrac's Comments, with different signal and noise power levels. An enhancement would be to introduce multipath effects via a fade simulator.

Once we have a complete characterization of the Teletrac receiver, I believe that we can analyze interference effects in a straightforward manner. As you point out, propagation models are well-known and documented in the technical literature. To quantify the effect of the Part 15 devices, I believe the best approach would be to develop a small set of "reference model" Part 15 interference sources with key characteristics (transmit power, bandwidth, hopping rates, etc.) that are representative of devices likely to populate the band.

In any event, I would encourage Teletrac to reconsider its position and meet with myself and others from the Part 15 community to plan a work program to quantify the potential for interference to Teletrac's system from Part 15 devices. I believe that such an activity is in the public interest, because only when we understand the interference potential can we provide sound technical guidance to the Commission in support of the Rule Making process.

We plan to fully discuss this issue during our winter Section meeting later this week. In addition, I have contacted Steve Schear, Chairman of the Part 15 Coalition, who has indicated that the first week in February may be a good time to hold the first planning meeting. I will contact you following our Section meeting to determine your availability to participate in this activity.

Regards,

Jay E. Padgett
Chairman, TIA MPC
Consumer Radio Section

cc:

Daniel L. Bart - TIA
Ralph A. Haller - Chief, FCC Private Radio Bureau
Steve Schear - Chairman, Part 15 Coalition
Eric J. Schimmel - TIA
Thomas P. Stanley - Chief Engineer, FCC

## ANALYSIS OF TELETRAC RECEIVER PERFORMANCE AND PART 15 INTERFERENCE

*Dr. Jay E. Padgett*
*Chairman, TIA Mobile & Personal Communications*
*Consumer Radio Section*

*October 22, 1993*

### EXECUTIVE SUMMARY

The FCC has adopted an NPRM in PR Docket 93-61, proposing to establish permanent provisions under Part 90 of its Rules for Automatic Vehicle Monitoring (AVM) systems in the 902-928 MHz ISM band. This proposal was made in response to a Petition filed in 1992 by PacTel Teletrac, which operates a wideband pulse-ranging AVM system in several metropolitan areas under the existing interim Part 90 Rules. The function of this system is to locate vehicles using a multilateration technique, whereby the vehicle responds to a narrowband high-power paging signal (the forward link) by transmitting a short (10-20 milliseconds) low-power wideband burst (the reverse link). This burst is received by multiple Teletrac base station receivers, each of which estimates the relative time of arrival (TOA) of the signal. Using the TOA estimates from the receivers and knowledge of their positions, the system can compute the location of the vehicle within several hundred feet.

One potential problem with this system is its vulnerability to interference from the unlicensed Part 15 devices that will be increasingly prevalent in this band. The purpose of this paper is to present an analysis of that interference and its effect on the Teletrac base station receivers. Teletrac contends that this interference will not present a problem to its system, but the analysis presented here shows otherwise. While the received signal power from a vehicle several miles from the base station will be on the order of -100 dBm (more or less depending on the base antenna elevation and the distance to the vehicle), the interference power from a Part 15 device several thousand feet from the base can be in the range of -40 to -60 dBm. The Teletrac receiver uses direct sequence modulation (a spread spectrum technique), which provides a processing gain that allows the receiver to operate satisfactorily with carrier-to-interference ratios as low as -25 dB (i.e., the desired signal 25 dB *below* the interference at the receiver). However, in the presence of interference that exceeds the desired signal by 40 dB or more, the receiver is operating far below its threshold and the TOA estimation error is so large that the receiver is essentially useless in contributing to the location estimate.* Widespread deployment of Part 15 devices, which are randomly located and uncontrolled,

* The simulation results reported by Teletrac in its Petition suggest that with a -40 dB carrier-to-interference ratio, the TOA estimation error can exceed 1 mile.

clearly could have a devastating effect on the performance and reliability of the Teletrac system.

The analysis provided here shows further that the relationship between bandwidth and capacity claimed by Teletrac and used to support the need for an 8 MHz reverse-link bandwidth is flawed. Teletrac claims in its Comments and Reply Comments that, based on the Cramer-Rao bound, which gives the theoretical lower limit on TOA estimation error, the required message length is inversely proportional to the square of the bandwidth, so that if the bandwidth is doubled, the message length can be reduced by a factor of four, quadrupling capacity. This claim, however, fails to account for the effect of the receiver threshold, and therefore is unrealistic.

As shown in this paper, the simulation results reported by Teletrac in its Petition, taken together with the receiver characteristic disclosed in Teletrac's Comments, suggest that once the receiver has reached its threshold, the minimum message duration varies as the inverse square root, rather than the inverse square, of the bandwidth. Consequently, to double the capacity, the bandwidth must be increased by a factor of four. Increasing the bandwidth from 4 MHz to 8 MHz will increase capacity by only about 40% (whereas capacity could be doubled by operating two systems on separate 4 MHz bands). Moreover, the Part 15 interference problem identified here cannot be solved even by increasing the bandwidth and holding the message length constant (thereby increasing the processing gain).

It is concluded that Part 15 devices represent a potentially serious threat to the viability of wideband pulse-ranging systems operating in the 902-928 MHz band, and regardless of the severity of the threat from Part 15 devices, increasing the bandwidth to gain capacity is not a worthwhile tradeoff. These conclusions imply that (1) the 902-928 MHz band, with its high potential for uncontrolled interference, may not be the appropriate band for wideband pulse-ranging systems such as Teletrac's, and (2) that 8 MHz per system may not be necessary in any event. These two points in turn suggest that another band should be sought for those systems, and the spectrum requirement may not be as great as has been assumed.

# ANALYSIS OF TELETRAC RECEIVER PERFORMANCE AND PART 15 INTERFERENCE

## 1. INTRODUCTION

This paper presents an analysis of the potential for interference from Part 15 devices that operate in the 902-928 ISM (Industrial, Scientific, and Medical) band into the the receivers used by Pactel Teletrac's wideband pulse-ranging system. Those receivers are designed to estimate the relative time-of-arrival (TOA) of a signal pulse from the vehicle to be located. The TOA estimates from multiple receivers at different locations then are used by the central system processor to estimate the location of the vehicle via multilateration.

The focus of this paper is the performance of an individual receiver operating in the presence of cochannel interference. The objective is to develop an understanding of the degree to which Part 15 devices can corrupt the TOA estimate of an individual receiver. Section 2 reviews the fundamental theoretical limit on the TOA estimation error (the Cramer-Rao bound) as well as the measured performance of the Teletrac receiver. Section 3 analyzes the receiver threshold effect and its implications on the ability to improve system throughput by increasing the bandwidth. Section 4 discusses propagation and the signal power received by the base stations from both the desired transmitter and from interfering Part 15 transmitters. Section 5 discusses the conclusions.

Reference is made to Teletrac's Petition [1] as well as the Comments [2] and Reply Comments [3] that Teletrac filed with the FCC in response to the NPRM on PR Docket 93-61 [4], and to the technical Appendices of [1] and [2].

## 2. TOA ESTIMATION ERROR FOR RECEIVER OPERATING ABOVE THRESHOLD

### *2.1 The Cramer-Rao Bound*

The receiver must provide an estimate of the TOA of a received signal burst. The measure of how effectively it does this is the rms TOA estimation error, denoted here by $\sigma_t$. As discussed in Appendices 1 and 2 of Teletrac's Comments, and also in the literature [5][6], the minimum mean-squared TOA estimation error is given by the Cramer-Rao bound as

$$\sigma_t^2 \geq \left[\beta^2 2E/N_0\right]^{-1}, \tag{1}$$

where $E$ is the total received energy in the message, $N_0/2$ is the two-sided noise spectral power density, and $\beta$ is the "effective bandwidth" or "Gabor bandwidth", given by

$$\beta^2 = \frac{\int_{-\infty}^{\infty} \omega^2 \,|\, S(\omega) \,|^2 d\omega}{\int_{-\infty}^{\infty} |\, S(\omega) \,|^2 d\omega}. \qquad (2)$$

$S(\omega)$ is the equivalent baseband signal spectrum (i.e., the Fourier transform of the signal). If the occupied bandwidth is limited to $W$ Hz, then the integrals in (2) would be taken between $-W/2$ and $W/2$.

If $C$ is the received RF carrier (desired signal) power and $T$ is the message length, then $E = CT$. As noted by Teletrac in Appendix 2 of its Comments[1] spread spectrum (direct sequence modulation) is used. This is to give a short pulse rise time without reducing the energy per message ("$E$" in eq. 1).

Assuming that cochannel interference has the same effect on receiver performance as additive Gaussian noise of the same total power,[2] and $B$ is the receiver noise bandwidth, then by definition $N_0 = N/B$, where $N$ is understood to be the total thermal noise plus cochannel interference power as seen by the receiver. Letting $T_C$ denote the chip duration, and defining $k_{BT} \triangleq BT_C$ (a constant which depends on the modulation and the degree of sidelobe truncation in the frequency domain[3]), (1) can be written as

$$\sigma_t^2 \geq \frac{T_C}{2k_{BT}\beta^2 T(C/N)}, \qquad (3)$$

where $C/N$ is the RF carrier-to-noise ratio.

Letting $k_\beta \triangleq \beta/B$, (3) becomes

1. "Theoretical and Field Performance of Radiolocation Systems," PacTel Teletrac, June 25, 1993, Appendix 2 of Teletrac's Comments [2].

2. With a spread spectrum system, this is a reasonable assumption for purposes of analysis, because the receiver correlates the received signal with the high-rate "pseudonoise" (PN) code waveform, which collapses the desired signal to its information bandwidth but spreads the interference over the entire spread bandwidth, and randomizes it.

3. This depends on the filtering of the received signal.

$$\sigma_t^2 \geq \frac{T_C}{2k_{BT}k_\beta^2 B^2 T(C/N)} . \qquad (4)$$

Clearly, $k_{BT}k_\beta = \beta T_C$, which is the same as the parameter "$a$" given in Appendix 2A of Teletrac's Comments.[4]. With $R = 1/T_C$ (the chip rate), (4) can also be expressed in the form of eq. A24 of Teletrac's Appendix 2A as

$$\sigma_t^2 \geq \frac{T_C}{2(k_{BT}k_\beta)^2 RBT(C/N)} . \qquad (5)$$

*2.2 Teletrac's Receiver Performance*

Teletrac's Petition and Comments suggest the following system parameters: $R$ = 1.7 Mchip/s, $T \approx 14$ milliseconds (70 messages/second), and $k_{BT}k_\beta = 1.875$ (corresponding to "Phase-shaped" BPSK modulation, from Table 1 of Teletrac's Appendix 2A).[5] Assuming $B = 2R$ (which appears consistent with eq. A25 of Teletrac's Appendix 2A), the Cramer-Rao bound on $\sigma_t$ for the Teletrac receiver would be roughly $\sigma_t \geq 1/\sqrt{C/N}$ (nanoseconds). This is close to (but slightly below) the "Cramer-Rao bound" curve shown in Figure 12 of Teletrac's Appendix 2, reproduced here as Fig. 1. The curve representing Teletrac's measured receiver performance is roughly described by

$$\sigma_t \approx \frac{2}{\sqrt{C/N}} \text{ (nanosec)} . \qquad (6)$$

Thus, the receiver's actual performance is about 6 dB worse than the Cramer-Rao bound calculated from the parameters estimated above, and about 5 dB worse than the "Cramer-Rao bound" curve in Fig. 1. It should be noted, however, that even the Cramer-Rao bound is design-dependent, because of the parameter $k_\beta$, which depends on the spectral shape of the

4. "Impact of Wide-band Co-channel Interference on the Accuracy of Hyperbolic Location," prepared by Emmanuel Wildauer, PacTel Teletrac, June 22, 1993, Appendix A to Appendix 2 of Teletrac's Comments [2].

5. The integration limits used to compute the values of $k_{BT}k_\beta$ for various modulation formats in Table 1 of Teletrac's Appendix 2A were not stated.

transmitted waveform.

## 3. THE EFFECT OF THE RECEIVER THRESHOLD

### *3.1 Mathematical Model*

As noted in Appendix 1 of Teletrac's Comments,[6] the performance of the receiver follows the form of the Cramer-Rao bound only as long as the carrier-to-noise ratio is above some threshold. This receiver threshold effect limits the ability to increase capacity (reduce message duration) by increasing the bandwidth. To understand this limitation, (1) can be written as

$$\sigma_t^2 = \frac{k_R}{2\beta^2 n \cdot [f(E_b/N_0)]}, \tag{7}$$

where $k_R$ represents the effect of receiver non-ideality during normal operation (i.e., a fixed dB offset from the Cramer-Rao bound). The parameter $n$ represents the number of information bits in the message,[7] and $E_b$ is the energy per bit, so $E = nE_b$. The function $f(\cdot)$ is defined as:

$$f(x) = x\,, \quad x \geq x_0$$

$$= f_2(x)\,, \quad 0 < x < x_0 \tag{8}$$

where $f_2(\cdot)$ is some unknown function and $x_0$ is the $E_b/N_0$ threshold, below which receiver performance no longer adheres to the form of the Cramer-Rao bound. For continuity, $f_2(x_0) = x_0$.

It is useful to normalize by defining a second function $g(\cdot)$ as

6. "Engineering Analysis of Cochannel Pulse-Ranging LMS Systems," Professor Raymond Pickholtz, June 28, 1993, Appendix 1 of Teletrac's Comments [2].

7. For a pure locating application (no information transmitted), $n = 1$. Eq. (7) presumes that for $n > 1$, a TOA estimate is generated for each received bit, then the $n$ estimates are averaged to yield an aggregate estimate. The variance of $n$ independent estimates will be less than that of each individual estimate by a factor of $n$.

$$g(\xi) \triangleq \frac{f(x_0\xi)}{x_0}, \tag{9}$$

hence, $f(x) = x_0 g(x/x_0)$. It is clear from (8) that for $\xi \geq 1$, $g(\xi) = \xi$ and for $\xi < 1$, $g(\xi) = g_2(\xi) \triangleq f_2(x_0\xi)/x_0$.[8]

If $T_b$ is the duration of a bit, then $E_b = CT_b$ (the total message duration is $T = nT_b$). Since the objective here is to explore the limitations on trading-off the bandwidth $B$ against the message duration $T$, it will be assumed that $C$, $N_0$, and $n$ are fixed. If $T_0$ represents the bit duration for which the receiver operates exactly at threshold, then by definition

$$T_0 = \frac{N_0 x_0}{C}. \tag{10}$$

Letting $\beta = k_\beta B$ as before, and aggregating fixed factors into a single constant, (7) becomes

$$\sigma_t^2 = \frac{k}{B^2 n[g(T_b/T_0)]} \tag{11}$$

where

$$k \triangleq \frac{k_R}{2k_\beta^2 x_0}. \tag{12}$$

Letting $\sigma_0$ represent the maximum acceptable value of $\sigma_t$, (11) gives

8. This is valid for any $f_2(x)$ for which a power series expansion exists; if $f_2(x) = \sum_{i=0}^{\infty} a_i x^i$ then $g_2(\xi) = \sum_{i=0}^{\infty} b_i \xi^i$, with $b_i = a_i x_0^{i-1}$.

$$g(T_b/T_0) = \frac{k}{B^2 n \sigma_0^2}. \tag{13}$$

If $B_0$ is the bandwidth for which $\sigma_t = \sigma_0$ when the receiver is operating at threshold (i.e., $T_b = T_0$), then from (13), with $g(T_b/T_0) = 1$,

$$B_0^2 = \frac{k}{n\sigma_0^2}. \tag{14}$$

Hence, (13) can be written as

$$g(T_b/T_0) = \left(\frac{B}{B_0}\right)^{-2}. \tag{15}$$

For $T_b \geq T_0$, $g(T_b/T_0) = T_b/T_0$ and (15) gives the relationship that $T$ $(= nT_b)$ decreases inversely with $B^2$, used by Teletrac to argue that maximum capacity (messages per second) increases as the square of the bandwidth (see, for example, p. 21 of Appendix 1 to Teletrac's Comments). However, for $T_b < T_0$, $g(T_b/T_0)$ behaves differently. To understand the effect of increasing bandwidth when $T_b < T_0$, the behavior of $g(\xi)$ for $\xi < 1$ must be understood.

This behavior can be inferred from the first analysis provided by Teletrac in Appendix 2 of its Petition for Rule Making,[9] and the receiver performance curve provided by Teletrac in Appendix 2 of its Comments (Fig. 1 of this paper). In the first analysis of Appendix 2 of its Petition, Teletrac illustrated the effects of cochannel interference with an idealized example. As shown in Fig. 2, the vehicle to be located was positioned at the center of a square 10 miles on a side, and a receiver base station was on each corner of the square. An interference source was 7000 feet to the left of the upper left base station (designated "site A" for purposes of this discussion). Teletrac computed the location error at the 95th percentile as a function of the RF power radiated by the interference source. A 5 watt transmit power with an antenna gain of -6 dBi was assumed for the vehicle, giving an ERP of 1.25 watts. Path loss

9. "Impact of Co-channel Interference on 900 MHz Wideband Pulse-ranging AVM System Performance," PacTel Teletrac, April 6, 1992, Appendix 2 of Teletrac's Petition [1].

was taken to vary as $d^4$ (i.e., 12 dB per octave or 40 dB per decade), and fading effects (multipath, shadowing) were ignored. Specific system parameters such as base tower height, chip rate, receiver noise bandwidth/noise figure, and message duration were not disclosed. However, it was stated that the cochannel interference source was assumed to be at ground level (presumably representing a mobile unit).

Based on the information available, the $C/I$ at each base station can be computed as a function of the RF power transmitted by the interference source, as shown in Figure 3.[10] Since the $C/I$ at the other 3 sites is much higher than site A, those receivers should contribute negligible error (several feet or less) to the location estimate, assuming that Teletrac's analysis used the receiver characteristic reported in Appendix 2 of its Comments.

It thus appears that site A is dominating the overall location estimation error. If this is the case, the location error vs. the $C/I$ at site A should accurately reflect the ranging error vs. $C/I$ performance of a single receiver. Fig. 4 shows the location error from the study in Teletrac's Petition vs. the $C/I$ at site A.[11] Also shown on Fig. 4 is the plot of $\sigma_r = 2/\sqrt{C/I}$ feet (dashed), which represents the rms ranging error (in feet) for Teletrac's receiver operating above threshold (i.e., $T > T_0$). The offset between the $\sigma_r$ curve and the location error curve presumably occurs because the error curve represents the ninety-fifth percentile, while the $\sigma_r$ curve represents the standard deviation of the estimation error. For most distributions, the ninety-fifth percentile will be more than one standard deviation above the mean (assuming an unbiased estimator, the mean is zero in this case).

The regression curve shown is actually the concatenation of a second-order regression (dashed) through the lower four points and a linear regression (solid) for all points except the lower three. This curve suggests that the receiver behaves in accordance with Fig. 1 provided $C/I$ is above a threshold of roughly -25 dB. As $C/I$ drops below -25 dB, the error begins to increase more rapidly than the inverse square-root of $C/I$. Once $C/I$ drops below about -30 dB, the error vs. $C/I$ characteristic becomes roughly inverse-square; that is, $\sigma_r \propto (C/I)^{-2}$. Thus, $\sigma_t$ varies as $1/\sqrt{C/I}$ for $C/I \geq -25\,\text{dB}$, and as $1/(C/I)^2$ for $C/I < 30\,\text{dB}$. The range $-25\,\text{dB} > C/I > -30\,\text{dB}$ is a transition region between the inverse square-root and inverse square variations. During discussions with Teletrac representatives [9], it was confirmed that a $C/I$ of -25 dB is roughly the practical lower carrier-to-noise limit of operation for the receiver.

This suggests that $f_2(x)$ can be modeled as $f_2(x) = x_0(x/x_0)^4$, so $g_2(\xi) = \xi^4$. Using this model for $g_2(\xi)$, (15) gives the tradeoff between $T_b$ and $B$ as

10. Fig. 3 is the same as Fig. 1 of the TIA Consumer Radio Section's Comments [7].

11. Fig. 4 is a modified version of Fig. 2 of the TIA Consumer Radio Section's Reply Comments [8].

$$T_b/T_0 = (B/B_0)^{-2}, \quad T_b \geq T_0 \tag{16a}$$

$$T_b/T_0 = (B/B_0)^{-1/2}, \quad T_b < T_0. \tag{16b}$$

Hence, the bandwidth-squared capacity increase applies only for $B \leq B_0$, and capacity cannot be increased as $B^2$ indefinitely. For $B > B_0$, the rate of increase slows to a square-root law, at which point it clearly is more efficient to increase capacity by using two separate frequency bands. Fig. 5 shows a piecewise-log-linear plot of $T_b/T_0$ vs. $B/B_0$.

*3.2 Receiver Threshold - Summary and Implications*

The results just derived may be summarized as follows:

1. The value of $T_b$ for which the receiver operates exactly at threshold is $T_0$, given by (10) as $T_0 = N_0 x_0 / C$. Reducing $T_b$ below $T_0$ (assuming $N_0$, $x_0$, and $C$ are fixed) will cause $E_b/N_0$ to drop below the threshold $x_0$, whether or not the bandwidth is increased.

2. The required bandwidth for an rms TOA estimation error of $\sigma_0$ when the receiver is operating at threshold (i.e., $E_b/N_0 = x_0$) is given by (14) as $B_0^2 = k/n\sigma_0^2$, where $k = k_R/2k_\beta^2 x_0$, $k_\beta = \beta/B$ (which depends on the shape of the desired signal spectrum), and $n$ is the number of information bits in the message. For a pure locating application, $n = 1$. For Teletrac's receiver, $\sigma_0 \approx 35$ nanosec for $C/I = -25$ dB, which appears to be the threshold for Teletrac's current-generation receiver parameters.

3. Given $T_0$, $x_0$, and $\sigma_0$ constant, $B$ can be traded off against $T_b$ according to (16a) and (16b). However, to decrease $T_b$ below $T_0$, $B/B_0$ must increase as the square of $T_0/T_b$. Thus, from a spectrum-efficiency perspective, it does not pay to increase $B$ above $B_0$. An increase in bandwidth to improve accuracy seems equally unjustified. Doubling the bandwidth of Teletrac's system would presumably decrease the rms TOA estimation error at threshold from about 35 nanoseconds to about 18 ns (i.e., an improvement in rms ranging error from 35 feet to 18 feet) in the absence of multipath, which seems to be past the point of diminishing returns. For the real-world environment in which Teletrac's system typically must operate, this improvement would be completely overshadowed by the uncertainties introduced by multipath. Without multipath, 35-foot accuracy would seem to be better than adequate. Hence, in either case, there seems to be no good reason to increase the bandwidth.

In light of these relationships, the "bandwidth squared" capacity increase claimed by Teletrac (see, for example, pp. 31-32 of Teletrac's Comments and p. 25 of Teletrac's Reply Comments) is illusory. If base stations are located to take maximum advantage of their operating range (that is, $E_b/N_0 = x_0$ at the perimeter of a base station's planned coverage for the design value of $N_0$), then capacity can only be increased as the square root of the bandwidth if $\sigma_t$ at the end-of-range is to be maintained constant. On the other hand, if there is "margin" designed into the link budget for the base stations, and $E_b/N_0 > x_0$ at the nominal end-of-range, then it could be claimed that $T_b$ could be reduced as the inverse-square of the bandwidth while maintaining $\sigma_t$ constant at the coverage perimeter. However, doing so simply reduces $E_b/N_0$ at the perimeter, reducing the margin. The additional capacity is being gained at the expense not only of bandwidth, but also of signal strength margin, which presumably was designed into the system for good reason. Indeed, capacity can also be increased by simply decreasing $T_b$ (and reducing the margin) without increasing the bandwidth, although $\sigma_t$ at the coverage perimeter will increase.

If the main signal impairment is an interference source of received power $I$, it could be argued from (14) that the effective noise spectral density is $N_0 = I/B$, so $N_0$ and hence $T_0$ decreases with bandwidth. While this is true for a single interference source, there will be numerous interfering Part 15 transmitters, randomly distributed in space and frequency. The greater the receive bandwidth of the AVM system, the greater the number of interference sources per unit area that will fall within the bandwidth. Moreover, as will be seen in the next section, the interference power that can be received from even a single Part 15 device is so high that bandwidth expansion is not a practical means to mitigate it (the impracticality of using bandwidth expansion to overcome the effect of a strong interfering signal is also discussed in Appendix 1 to Teletrac's Comments, pp. 37-38).

## 4. PROPAGATION AND RECEIVED SIGNAL POWER

### *4.1 Desired Signal Power*

In the mobile radio environment, there often is no line-of-sight path between a vehicle and a base station several miles away, and the signal propagates via reflection, diffraction, and penetration through obstructions. The received signal often is modeled as having a median that varies as $d^{-\gamma}$, where $d$ is the base-to-mobile distance and $\gamma$ is the path loss exponent. Random large-scale variations due to "shadow fading" and small-scale variations due to multipath[12] are superimposed on the variations in the median due to changes in $d$.

Models such as that of Hata [10], which is based on data gathered by Okumura [11], predict the median path loss as a function of $d$ given the frequency, antenna elevations, and type of environment (i.e., urban, suburban, rural). Using the Hata model, the median received power (in dBm) can be expressed in the form

12. The terms "large-scale" and "small-scale" refer not to the magnitude of the signal strength variations associated with these phenomena, but rather to the distances over which the variations occur. In a severe multipath environment, variations due to multipath are quasi-periodic with minima a half-wavelength apart, on average. Conversely, the variations due to shadow fading occur over many wavelengths (typically tens or hundreds of feet).

$$C = P_{TX} - \alpha - 10\gamma \log d + g_B , \qquad (17)$$

where $P_{TX}$ is the ERP of the mobile in dBm, $g_B$ is the gain of the base antenna in dB, and $\alpha$ and $\gamma$ are given by the Hata model; $\alpha$ depends on frequency, antenna elevations, and environment, and $\gamma$ depends on the antenna elevations.

The following table shows $\alpha$ and $\gamma$ for various base antenna elevations in the "suburban" environment at 915 MHz, and the median received power for $d = 5$ miles, assuming a half-wave dipole on the base (2.15 dB gain), and a transmit power (from the vehicle) of 1 watt ERP. For an urban area, the median received power levels would be 10 dB lower at this frequency.

| $h_B$(ft) | $\alpha$ (dB) | $\gamma$ | $C$, dBm ($d = 5$ mi) |
|---|---|---|---|
| 50 | 128.3 | 3.72 | -122.1 |
| 100 | 123.7 | 3.52 | -116.2 |
| 200 | 119.2 | 3.32 | -110.2 |
| 300 | 116.5 | 3.21 | -106.7 |
| 400 | 114.6 | 3.12 | -104.3 |
| 500 | 113.1 | 3.06 | -102.4 |

These levels represent the median signal strength that a Teletrac base station would expect to receive from a mobile 5 miles away. As can be seen, the median received signal is on the order of -100 to -120 dBm, depending on the base antenna elevation. The median received signal level varies roughly 9 to 11 dB per octave with $d$. For example, with $h_B = 200$ ft, halving $d$ to 2.5 miles would increase $C$ by roughly 10 dB, to about -100 dBm.[13]

Assuming the system is engineered for a noise floor of -90 dBm (see p. 9 of Appendix 1 to Teletrac's Comments), then a -25 dB carrier-to-noise threshold would allow the system to operate with a received signal strength of -115 dBm, which gives a range of about 5 to 10 miles, depending on the tower height. In reality, some margin must be allowed for fading effects, but that will be ignored here in the interests of simplicity.

*4.2 Interference Power From Part 15 Devices*

The path loss between a Part 15 device at street level and several miles from a Teletrac base station can be modeled using Hata's formulas. However, the Hata model does not apply for separations less that 1 km, and microcell propagation models must be considered. Such

13. The variation of $C$ with $d$ is $3\gamma$ dB per octave; that is, if $d$ doubles, $C$ decreases by $3\gamma$ dB.

models are discussed by Green [12] and by Green and Hata [13], who observe that in some cases (such as on a roadway when a line-of-sight path is present) the "two-path" model gives reasonably accurate results. This model assumes a direct ray and a ground-reflected ray, with the total received field being the complex phasor sum of the two. The reflected ray thus can positively or negatively reinforce the direct ray, depending on the phase relationship between the two. The ground-reflection coefficient can be calculated as a function of the incidence angle, as discussed by Jordan and Balmain [14].

Fig. 6 shows the received power vs. $d$ for $h_B$ = 100 ft, $f$ = 915 MHz, and $P_{TX}$ = 1 watt (the maximum transmitted power for a Part 15 device operating in the 902-928 MHz band under §15.247 of the FCC Rules). The parameters $\sigma$ and $\epsilon_r$ are the conductivity (mhos/meter) and relative dielectric constant assumed for the ground. As can be seen, the reflection causes oscillations of 5 to 10 dB about the free-space ($d^{-2}$) level, until the "break point" (roughly a mile here) is reached and the received signal begins to drop off as $d^{-4}$. For distances up to a mile, the received interference power lies between -30 dBm and -60 dBm. Figs. 7 and 8 show similar curves for 200 ft and 400 ft base station antenna heights, respectively. Fig. 9 shows the received signals for all three heights together.

The levels of interference shown by these curves will create a serious problem for receivers such as Teletrac's. To illustrate, assume that receiver coverage boundaries are designed for a noise floor of -90 dBm (i.e., a received signal power of about -115 dBm). A received interference level of -55 dBm, which corresponds to an interference source roughly 4000 feet from the base for a two-path model with $h_B$ = 100 ft, would require an increase of 35 dB in the desired signal level, which would decrease the range by roughly a factor of 10, and the coverage area by a factor of 100. This effectively would remove the base station from service.

Finally, it is reasonable to assume that because of the interference-prone, uncontrolled nature of the 902-928 MHz band, many Part 15 devices will be designed with some degree of frequency agility, to allow them to avoid interference so as to provide their customers with clear communication channels. Unfortunately, such capability will not be of much help in reducing their interference to a system such as Teletrac's, because it depends on the ability to detect an interfering signal. The reverse-link signal in Teletrac's system will emanate from a vehicle near the ground, will be spread over a wide bandwidth, and will be of very short duration. Hence, it is unlikely that it will be seen by the Part 15 device, which will have no way of knowing that the band is "in use," and will therefore have no reason to avoid transmitting in it.

*4.3 Effect of Frequency Hopping and Direct Sequence Modulation of the Part 15 Signal*

Section 15.247 of the FCC Rules allows Part 15 devices operating in the 902-928 MHz band to use up to 1 watt of RF transmit power providing either direct sequence modulation or frequency hopping is used. The purpose of this subsection is to discuss the effect of these requirements on the potential for interference to Teletrac's receivers.

Direct sequence modulation spreads the transmitted signal power over a bandwidth much greater than the information bandwidth. Section 15.247 requires a "spread" bandwidth of at least 500 kHz and a processing gain of at least 10 dB, which means that the spread bandwidth must be roughly ten times the information bandwidth, or more. The spectrum-spreading can reduce the interference caused by the Part 15 device if the "spread" Part 15 signal has a bandwidth greater than that of the victim receiver, which will "see" only a fraction of the power from the Part 15 device. For a wideband receiver such as Teletrac's, however, it will not have much impact on the interference potential in many cases. Consider, for example, a system with an information bandwidth of 100 kHz and a spread bandwidth of 1 MHz. Depending on channel alignment, the entire spectrum of the Part 15 transmitter can fall within the receive bandwidth of the Teletrac receiver. Further, several such Part 15 devices can fall within the Teletrac receiver's passband without interfering with each other. Hence, unless it spreads its signal over a very wide band, a Part 15 device using direct sequence modulation poses essentially the same interference threat to the Teletrac system as it would using conventional narrowband modulation.

The frequency hopping requirements in §15.247 require that a device operating in the 902-928 MHz band use a hop sequence consisting of at least 50 randomly-selected frequencies, and transmit on each frequency no longer than 400 milliseconds at a time. This means that on the average, a single frequency hopper will be operating within a given 8 MHz bandwidth roughly 30% of the time. If there are $k$ frequency hoppers operating near a Teletrac receiver, the probability that at least one of them is within a given 8 MHz bandwidth at any given time is $1 - 0.7^k$, assuming their hop sequences are random and mutually independent. Thus, if there are 2 hoppers, the probability that a given 8 MHz band is "clear" is 49%; for 3 hoppers it is 34%, and for 4 hoppers it is 24%. It should also be noted that this problem will not tend to be alleviated to any great extent by interference among the hoppers themselves. First, several hoppers may have good propagation paths to the Teletrac receiver due to its high elevation, but poor paths to each other, if they are near the ground. They therefore may cause no discernible interference to each other. Second, due to the wide bandwidth of the Teletrac receiver, a number hoppers with relatively narrow channel bandwidths (e.g., 100-200 kHz) can operate within the same Teletrac receiver bandwidth simultaneously without causing cochannel interference to each other, even if they are operating in close proximity.

It appears, therefore, that the spread spectrum requirement in §15.247 associated with the allowed 1-watt transmit power will not significantly mitigate the interference threat posed by Part 15 devices to receivers of systems such as Teletrac's. Further, the wider the bandwidth of the AVM receivers, the more severe the problem.

## 5. CONCLUSIONS

This discussion has focussed on the receiver in a Teletrac base station, the function of which is to estimate the time-of-arrival (TOA) of a signal pulse received from the vehicular transmitter. Of interest is the relationship between the TOA estimation error and the interference sustained by the base receiver. The performance of the Teletrac receiver (as given in Teletrac's Comments [2] was reviewed and compared to the Cramer-Rao bound, which gives a lower limit on the rms TOA estimation error as a function of the RF carrier-to-noise ratio (CNR). In both cases, the rms TOA estimation error varies inversely with the square root of the CNR, and the Teletrac receiver's performance is within about 5-6 dB of the Cramer-Rao bound. However, the inverse-square-root relationship only applies when the CNR is above the receiver's threshold, which for the current version of the Teletrac receiver, appears to be about -25 dB. When the CNR drops below this level, the rms TOA estimation error seems to vary roughly as the inverse-square of the CNR. This threshold effect has not been taken into account in the arguments of bandwidth-versus-capacity tradeoffs made by Teletrac. Taking into account the threshold effect, it appears that the claimed "bandwidth squared" capacity gain is illusory, as explained in section 3. In fact, the maximum capacity of a system will increase only as the square root of the bandwidth, given a maximum allowable rms TOA estimation error. Hence, the argument that more bandwidth is needed to support larger capacities does not appear valid.

Section 4 provided calculations of desired and interfering signal power as seen by a Teletrac receive base station, and it was shown that a Part 15 device with a line-of-sight path to a base station (which may not be unusual, considering that the base stations are typically elevated several hundred feet above the terrain, to maximize coverage) can deliver interference power levels of -30 to -60 dBm into the receiver, which will essentially render the receiver useless. This analysis considered only a single interference source, but as the penetration of Part 15 devices grows, it may not be uncommon for several such devices to fall within the wide Teletrac reverse channel passband simultaneously. Clearly, the wider the Teletrac reverse channel bandwidth, the greater the vulnerability to uncontrolled interference.

Based on the results given here, it is concluded that Part 15 devices in the 902-928 MHz band constitute a serious interference threat to systems such as Teletrac's that depend on reception of relatively weak signals. The question of how often interference incidents will occur is beyond the scope of this paper, because that depends on the penetration achieved by Part 15 devices. However, the increase in that penetration during the next 3-5 years is expected to be considerable, especially for consumer items such as cordless telephones, as well as wireless business systems. It therefore is important that this impending problem be acknowledged and taken into account in proceedings related to PR Docket 93-61.

Finally, it should be noted that as Teletrac modifies and refines its designs, the parameters used in the calculations presented here may change, but the fundamental conclusions will not. One such change might be a modified pulse shape to give a waveform that provides better ranging performance than the BPSK waveform that the current generation of Teletrac's equipment apparently uses.[15] The use of a more efficient ranging waveform would increase the constant $k_\beta$, allowing more accurate TOA estimation with a given RF bandwidth. This

15. Because of the parabolic weighting function in (2), signal spectra that concentrate most of the power at the outer edges of the band will have larger values of $\beta$ and give better TOA estimates, given the bandwidth constraint (this is discussed in [5], pp. 405-407).

would actually *reduce* the amount of bandwidth needed for a given level of performance. Another potential change is an increase in the direct sequence chip rate, which would result in an increase in the RF bandwidth, given a fixed $k_\beta$. This would affect the $C/I$ threshold, but not the $E_b/N_0$ threshold. One reason for this would be to reduce the message duration, thereby increasing capacity. However, as already discussed, once the bandwidth is sufficiently higher to provide the required TOA estimation accuracy at end-of-range, increasing bandwidth further to reduce message duration does not seem to be a spectrum-efficient tradeoff.

These conclusions imply that (1) the 902-928 MHz band, with its high potential for uncontrolled interference, may not be the appropriate band for wideband pulse-ranging systems such as Teletrac's, and (2) that 8 MHz per system may not be necessary in any event. These two points in turn suggest that another band should be sought for those systems, and the spectrum requirement may not be as great as has been assumed.

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